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Fire cycle of the Canada's boreal region and its potential response to global change

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Abstract: Interactions of fire cycle and plant species' reproductive characteristics could determine vegetation distribution pattern of a landscape. In Canada's boreal region, fire cycles before the Little Ice Age (c. 1850s) ranged from 30–130 years and 25–234 years afterwards until the settlement period (c. 1930s) when longer fire cycles occurred in response to climatic change and human interference. Analysis indicated that fire cycles were correlated with growing season (April-October) temperature and precipitation departure from the 1961-1990 normal, varying by regions. Assuming that wildfires will respond to future warming similar to the manner during the past century, an assessment using climatic change scenarios CGCM1, CGCM2 and HadCM2 indicates fire cycles would divert to a range of 80-140 years in the west taiga shield, more than 700 years for the east boreal shield and east taiga shield, and 300-400 years for the boreal plains in 2050.

Keywords: Boreal forest; Fire cycle; Global change; Spatial variability

Instruction

Fire cycle (van Wanger 1978) or fire rotation (Heinselman, 1973) is an indicator of fire frequency measuring the time (years) required to burn an area equal in size to the area under consideration. It has been an important component in maintaining boreal ecosystems for the past 10 000 years since the last glaciation (Payette *et al*. 1985). Ecosystems adapted to the various fire regimes in the boreal region along the migration of species from south and other refugees of glacier, but they are not necessarily in equilibrium with the climate (Overpeck *et al*. 1990; Campbell *et al*. 1993). Studies revealed a complex interaction among landscape, fire regimes, and vegetation types (Bergeron *et al*. 1993; Suffling 1995; Hely *et al*. 2001). Changes in fire cycles have significant consequences on landscape pattern by affecting regenerating pathways of forest after fires. Interactions of fire cycle and species' reproductive characteristics could determine vegetation distribution pattern of a landscape (Suffling *et al*., 1988; Bergeron and Dansereau, 1993; Johnson at al. 1995; Suffling 1995). For instance, an increase of fire frequency would cause shifts of vegetation zones northwards and increases of deciduous species (e.g., poplar) importance in landscape of central Canada (Suffling 1995) and coniferous dominance in the east (Bergeron *et al.* 1993; Gauthier *et al*. 1996).

On daily and monthly bases, fire occurrence is closely related to weather conditions, while fire regime at decadal to century scales is coupled with climate (Johnson *et al.* 1991; Johnson 1992; Larsen 1996). Over the past few hundred years, climate has changed dramatically across Canada (Grove 1988; Gullett *et al.* 1992). Studies revealed consequent changes in fire cycles and feedbacks linking landscape pattern of the boreal ecosystems (Wein *et al.* 1983; Suffling *et al.* 1988; Baker, 1992, 1995; Johnson *et al*. 1995; Razt 1995; Campbell mand Flannigan 2000; Weir *et al*. 2000). There were also attempts to project future fire activities by using fire weather index (FWI) or its derivation of seasonal severity rating (SSR) and yet changes in fire frequency (fire cycle is an indicator of fire frequency) were difficult to quantify because of the poor correlation between burned areas and SSR (Flannigan *et al.* 1991; Flannigan *et al.* 1998). Moreover, fire cycle is a long-term and cumulative indicator of fire frequency over a large area while FWI/SSR indicates daily representation of fire danger at a specific location (Flannigan *et al.* 1991; Weber *et al.* 1997).

On the other hand, society's perception of fire has changed as well. Policy concerning wildfire has evolved from suppression to current prescribed burning (e.g., using fire as a management tool for forest ecosystem management), and there are some forms of fire management programs in place over the boreal region (Ward and Mawdsley, 2000). Because forested landscape pattern at any moment is a reflection of and a mosaic from the past dynamics fire cycles (Larsen 1996; Johnson *et al*. 1995, 1998). Changes in policy would have had profound impacts on landscape pattern (Baker 1992, 1995; Beverly 1998; Weir and Johnson, 1998; Ward *et al*. 2001). Thus, formulation of forest fire management has to consider past changes in fire cycles and the potential impact of climatic change in the near future.

This study is to summarize the changes in fire cycles and the spatial variability over the past century across Canada's boreal region. Multiple regressions were employed to provide insight in the relationships between fire cycle and climatic variables (e.g.,

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temperature and precipitation). By using developed empirical relationships and the widely used climate change scenarios of CGCM1, CGCM2, and HadGM2, potential changes of fire cycles in response to climate change and the implications on forest management are discussed afterwards.

Data collections and analysis

The authors extracted data from the literature and the survey was intended to be as inclusive as possible (Table 1; Fig. 1). The compiled dataset included publications in which fire cycles were explicitly estimated or from which fire cycles could be derived. Studies have revealed changes in fire cycles attributable to climatic change and human activities (e.g., fire suppression). To demonstrate the relationships between fire cycle and climatic conditions, we acquired Canada's historic climate dataset of the past century from Environment Canada (New *et al*. 2000). Data in fire season (defined as the time period of April-October) including mean temperature and total precipitation and the departures from the 1961–1990 normals were derived from the dataset. Considering that fire cycle could be significantly different by inclusion of one or few fire seasons (Beverly 1998), we also derived the maximum temperature and its departures from the 1961–1990 normal for each fire cycle study site over its respective time period of consideration. Because the climatic dataset was limited in the time period of 1901-1998, the analysis was carried out on the study sites with fire cycle estimations within this period (Table 1). Selection of the climatic variables was also limited by the data source, which included only monthly temperature and precipitation (New *et al*. 2000). Annual mean temperature departure from the 1961–1990 normal in the region was also obtained from Environment Canada (Gullett *et al*. 1992).

Table 1. Fire cycle studies in the Canada's boreal region

Eco Zone (ESWG, 1996)	Location	Total study area (km^2)	Record type	Dominant species	Record period	Fire cycle (a)			Reference
						Before Little Ice Age (c. 1850)	Settlement epoch (c. 1930s)	Suppression era	
Boreal Cordillera	Kluane National Park, Yukon	1541	Aerial photos	White spruce	1890-1970			160	Alexander and Dube 1983
	Kluane National Park, Yukon	22100	Aerial photos, fire scars	White spruce	1880-1980			179	Hawkes 1983
Taiga Plains	Inuvik, NW territories	140 km transect	Stand samplings	Black spruce	1970's			100	Black and Bliss 1976
West Taiga Shield	Abitau-Dunvegan lakes, NW Territories	4100	Stand samplings, fire scars	Black spruce, paper birch	~1976			100	Maikawa and Kerhaw 1976
	Caribou Range, NW Territory	105000	Fire reports	Black spruce	1966-1972			110	Johnson and Rowe 1975
	Great Slave Lake, NW Territories	105000	Samplings, fire reports, fire scars	Black spruce, jack pine, white spruce	1966-1975			150	Johnson 1981
	Whirlwind Lake, NW Territories	25	Fire reports	Jack pine, black spruce	1966-1972			37	Johnson 1979
	Siltaza Lake, NW Territories	25	Fire reports	Black spruce, jack pine	1966-1972			102	Johnson 1979
	Rutledge Lake, NW Territories	100	Fire reports	Black spruce, jack pine	1966-1972			70	Johnson 1979
	Pilot Lake, NW Territories	100	Fire reports	Jack pine, black spruce	1966-1972			51	Johnson 1979
Boreal Plains	Candle Lake, Saskatchewan	Samplings	Stand ages	Balsam fir, paper birch, black spruce	~1970s			120	Dix and Swan 1971
	Prince Alberta National Park, Saskatchewan	1898	Time-since-fire map	many boreal species	1745-1995	25	25	645	Weir *et al.* 2000
	Prince Alberta National Park, Saskatchewan	1563	Time-since-fire map	many boreal species	1745-1995	15	75		Weir *et al.* 2000
	Northeastern Alberta	73600	Fire records	Aspen, black spruce, white spruce	1961-1996			482	Cumming 2001
	Wood Buffalo National Park, Alberta	44800	Fire reports	Black spruce	1950-1985			69	Larsen and MacDonald 1995
	Wood Buffalo National Park, Alberta	44870	Sampling, fire maps, fire scars	Black spruce, white spruce, jack pine	1750-1989	38		63	Larsen 1997
	Wood Buffalo National Park, Alberta	Samplings	Fire-origin map	White spruce	1951-1995			186	Timoney *et al.* 1997
	Rutledge Lake, Northwest Territories	105000	Fire scars	Jack pine, black spruce				100	van Wagner 1978
	west-central Alberta	6500	Stand ages	Pine, white spruce	1915-1960		50	65	van Wagner 1978
	Foothill model forests, Alberta		Aerial photos		1790-1950			80	Andison 1997
West Boreal Shield	Northern Ontario	1,100 km transect	Fire records	Boreal species			40		Suffling 1995
	Wabakimi Provincial Park, Ontario	8920	Fire reports	Jack pine, black spruce	1858-1978		37	360	Beverly 1998
	Northwest Ontario	300 km transect	Fire reports	Jack pine, black spruce	1921-1976			120	Suffling *et al.* 1988

Continue Table 1.

Eco Zone (ESWG, 1996)	Location	Total study area (km^2)	Record type	Dominant species	Record period	Fire cycle (a)			Reference
						Before Little Ice Age (c. 1850)	Settlement epoch (c. 1930s)	Suppres-sion era	
	Northern Ontario	43506 inventory stands	Forest resource inventory, fire reports	Black spruce, jack pine	1860-1975		60	120	Suffling *et al.* 1982
East Taiga Shield	Newfoundland		Fire records	Boreal forests	1910-1970			400	Wilton and Evans 1974
	Southeastern Labrador, Newfound-land	48500	Aerial photos, fire reports	Black spruce	1870-1979			500	Foster 1983
	Northern Quebec	4725	Fire scars, aerial photos	Black spruce	1920-1984			100	Payette *et al.* 1989
	Northern Quebec	14850	Fire scars, aerial photos	Black spruce	1920-1984			180	Payette *et al.* 1989
	Northern Quebec	17100	Fire scars, aerial photos	Black spruce	1930-1984			1,460	Payette *et al.* 1989
East Boreal Shield	Central Quebec	3844	Fire-origin map	Boreal forest species	1700-1999	69	123	273	Bergeron *et al.* 2001
	Laurentian Highlands, Central Quebec	large area	Fire records, stand samplings	Spru	1972-1974	70		100	Cogbill 1985
	Abitibi east, Quebec	3294	Fire-origin map	Boreal forest species	1850-1999		86	191	Bergeron *et al.* 2001
	Barron Township, Ontario	186	Fire scars, reports	White pine, aspen	1939-1974	80		70	Cwynar 1977 1978
	Lake Duparquet, Quebec	50	Fire scars	Red pine stands	1800-1982	30		68	Bergeron and Brisson 1990
	Lake Duparquet vicinity, Quebec	2000	Fire scars	White spruce, aspen	1760-1988	63		99	Bergeron 1991
	Islands of Lake Duparquet, Quebec	50	Fire scars	White spruce, balsam fir	1729-1988	74		112	Bergeron 1991
	Abitibi west, Quebec	15793	Fire-origin map	Boreal forest species	1700-1999	83	146	325	Bergeron *et al.* 2001
	Lake Abitibi model forest, Ontario	8245	Fire-origin map	Boreal forest species	1700-1999	132	234	521	Bergeron *et al.* 2001
	Intensive and measured fire man-agement zones, Ontario	492810	Fire reports	Boreal species	up to 2000		65	604	Ward *et al.* 2001

Multiple regression analyses on the relationship between fire cycles and climatic variables were initially conducted using fire cycle studies (Table 3). Since the total precipitations are different across Canada's landmass (Stone *et al.* 2000), changes in precipitation (e.g., departure from the 1961−1990 normal) were calculated as the percentages of the 1961−1990 normal for the respective ecozone. That would also be compatible with the climate change scenarios (e.g., decrease or increase in precipitation by percentages). Multiple regression analyses were conducted to derive the relationship between fire cycle and climatic variables over the past century thereafter. We focused the study in the west taiga shield, boreal plains, east boreal shield and east taiga shield, because there were too few fire studies in other ecozones (Fig. 1).

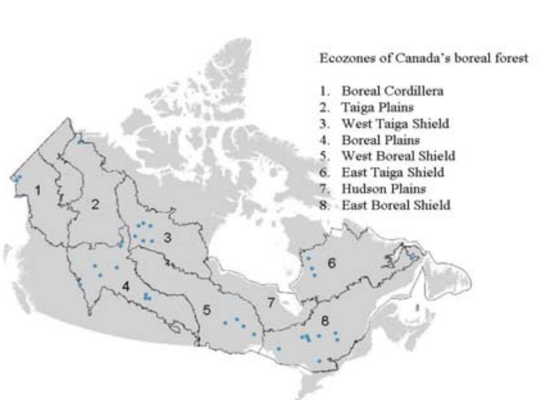

Fig. 1 Ecozones of Canada's boreal forest region (ESWG 1996) and locations of fire cycle studies (Table 1)

Climate change scenarios of CGCM1, CGCM2, and HadGM2 were derived from the websites of IPCC and the Canadian Institute for Climate Studies (http://ipcc-ddc.cru.uea.ac.uk/; http://www.cics.uvic.ca/scenarios/index.cgi? Other_Data; Price *et al.* 2001). Projected changes in growing season (April-October) temperature and total precipitation in 2050 were derived from the datasets and utilized to assess possible changes in fire cycle using the developed empirical relationships using fire cycle studies (Table 4).

Results and discussion

Spatial variations and temporal changes of fire cycles

Studies revealed that fire cycles were less than 80 years except one report of 132 years (Bergeron *et al.* 2001) in the eastern Ontario before the Little Ice Age (c. 1850s), (Tables 1, 2). Since then, reported fire cycles were greater than 400 years in the east and highly varied in the rest of the Canada's boreal region. They were in a range of 25–234 years before the large-scale settlement (c. 1930s) but not significantly different from these before the Little Ice Age at the continental scale. Fire cycles had dramatically increased for the past few decades especially in the eastern region and the diversion between the east and west had been established. Changes of fire cycles during the past 20 years (1980-2000) suggested that shorter fire cycles were less than 100 years in drier west and longer ones greater than 700 years in the moister east boreal shield (Table 2).

Spatial variability of fire cycle indicated a closely relationship among fire cycle and landscape pattern (Bergeron 1991). For

instance, fire cycles were significantly different among different vegetation types within a landscape (Suffling *et al*. 1982; Larsen 1997; Timoney *et al*. 1992). A study in a transect of north Ontario (Suffling *et al*. 1988) revealed varying fire cycles from 110 to more than 1000 years, in a short distance. That indicated the influence of underlying heterogeneity of landscapes on fire cycle. A small sampling area over a short time period of consideration could result in significant differences in estimated fire cycles because one fire incident might burn over the entire area of consideration. For instance, fire cycles were 742 years in the Wabakimi Provincial Park of Ontario between 1979 and 1994 and decreased to 202 years if areas burnt in 1995-1996 were included in the estimation (Beverly 1998).

Relationship between fire cycle and climatic variables

A nation-wide study on the changes in temperature revealed a statistically significant increase of 1.1°C during the period 1895-1991 (Gullett *et al*. 1992). There were three phases, warming periods before 1940s and after 1970s and one cooling period in between over the past century. Coincidently these phases corresponded well the epochs when fire cycles changed (Gullett *et al*. 1992; Table 2) and shorter fire cycles were observed in ecozones with larger increases in temperature over the past century (Table 2).

Table 2. Fire cycles by ecozone (ESWG 1996)

Ecozone	Fire cycle (a) A				Temperature change (1895-1991) B
	Before Little Ice Age (c. 1850)	Settlement epoch (c. 1930s)	Suppression era	1980-2000	
Boreal Cordillera			160-179	264	0.8
Taiga Plain			100	90	1.7 *
West Taiga Shield			37-150	47	1.7 *
Boreal Plain	15–38	25–75	63–645	132	1.3 *
West Boreal Shield		40–60	120–360	88	1.3 *
East Taiga Shield			100–400	162	0.5
Hudson Bay				307	0.5
East Boreal Shield	30–132	65–234	68–604	728	0.5
Total				145	1.1 *

Notes: A----Fire cycles for the periods of before Little Ice Age, Settlement epoch, and Suppression era were; extracted from the literature. Those of 1980-1990 were estimated using areas burnt from Frnech; *et al*. (2001) and Amiro *et al*. (2001) for the time period 1980-1994 and AVHRR hotspot for 1995-2000; Indicating changes in fire cycle. B----Data derived from Gullett and Skinner (1992). *----Variables utilized in multiple regression analysis.

However, there were no significant correlations between fire cycles and temperature or other climatic variables in the fire cycle study sites over the respective time period nation-wide. Rather, relationships at ecozone level were evident (Table 3). In the west taiga shield, fire cycle was related to various temperature measurements and precipitation departure from the 1961-1990 normal ($r^2 = 0.36$), (Table 4). We chose the mean temperature to conduct a multiple regression analysis and obtained the following equation to describe their relationship in the ecozone:

$$F_C = 296.64 - 41.58 \times T\mathrm{m} + 9.07 \times \Delta P \quad (r^2 = 0.56) \qquad (1)$$

where, F_C, Tm and ΔP were fire cycle, mean temperature and changes (%) of precipitation over the 1961-1990 normal, respectively.

In the east boreal shield and east taiga shield ecozones, fire cycle seemed to correlate with the maximum temperature departure from the 1961-1990 normal ($r^2 = 0.30$) and precipitation departure from the 1961-1990 normal (Fig. 3A, $r^2 = 0.24$), (Table 4). Inclusion of the estimated fire cycles using fire statistics of 1960-2000 would increase (r^2) from 0.35 to 0.42, respectively. It indicated the importance of few warm seasons in determining fire cycle in the region. A multiple regression was conducted and the relationship between fire cycle and climatic variables could be described using the following equation.

$$F_C = 818.77 - 174.15 \times \Delta T\mathrm{x} + 42.30 \times \Delta P \quad (r^2 = 0.56) \quad (2)$$

where, F_C, ΔTx and ΔP were fire cycle, maximum temperature departure from the 1961−1990 normal, and precipitation departure from the 1961−1990 normal, respectively.

Relationships between fire cycle and the maximum temperature departure from 1961−1990 normal ($r^2 = 0.30$) and the total precipitation departure from the 1961-1990 normal ($r^2 = 0.39$) were also observed in the boreal plains ecozone (Table 4). A multiple regression analysis revealed the following equation to predict fire cycle in the region.

$$F_C = 909.90 - 384.39 \times \Delta T\mathrm{x} + 20.48 \times \Delta P \quad (r^2 = 0.49) \quad (3)$$

where, F_C, ΔTx and ΔP were fire cycle, maximum temperature departure from the 1961−1990 normal, and precipitation departure from the 1961−1990 normal, respectively.

Table 3. Correlation (r^2) between fire cycles and climatic variables by ecozone (ESWG 1996)

Ecozone (ESWG, 1996)	Mean Temperature (°C)	Mean Precipitation (mm)	Maximum Temperature (°C)	Maximum precipitation (mm)	Mean temperature departure from the 1961-1990 normal	Total precipitation departure from the 1961-1990 normal	Maximum temperature departure from the 1961-1990 normal
West Taiga Shield	0.72*	0.04	0.46	0.00	0.52	0.36*	0.71
East taiga shield east boreal shield	0.05	0.02	0.04	0.00	0.00	0.24*	0.30*
Boreal plains	0.11	0.34	0.00	0.27	0.16	0.39*	0.30*

Notes: *----Variables utilized in multiple regression analysis.

While there were too few fire studies to characterize the relationships between fire cycle and climatic variables in other ecozones, the analyses here suggested that there were different dominant climatic variables in different regions and the importance of few warming seasons over the 1961−1990 normal climatic conditions in determining regional fire cycles. That explained why inclusion of few warming seasons might greatly change the fire cycle of a region (Beverly 1998). That also implied that over a large and relatively uniform landscape (e.g., ecozone) fire cycle over a certain time period had been relating

to the climatic fluctuation or changes at the site of consideration. Of course, fire cycles were different in various sites over the referenced time period (i.e., 1961−1990) in contrast to the result from the equations. That might result from factors other than climate such as vegetation types, fuel loading and topography (Johnson 1992; Cumming 2001; Timoney *et al*. 1997).

Potential changes of fire cycles under climate change scenarios

Changes in climatic conditions affected fire cycles in the past (Johnson *et al*. 1991; Johnson 1992; Larsen 1996). Projected fire weather index (FWI) and its derivation of seasonal severity rating (SSR), under doubling CO_2 would decrease in the east and area burned could be increasing by 40%–50% in the west (Flannigan *et al*. 1991; Weber *et al*. 1997; Flannigan *et al*. 1998). Assuming that there is a one to one relationship between FWI and area burned (Michael Flannigan, personal communication), fire frequency would likely decease by 10%-15% (a fire cycle of more than 700 years) in the east and increase (a fire cycle of 60–80 years considering 40%–50% increase in area burning) in the central and western Canada. Uncertainty remains on the assumption of the relationship between FWI, a short-term index of climatic conditions, and fire cycle, a long-term and cumulative indicator of fire activities.

Using the derived relationships between fire cycles and climatic variables (Eqs. 1–3) and climate change scenarios (Table 4), we assessed the possible changes of fire cycles responsive to climatic warming in the three ecozones. The relationships were empirical and the underlying assumption was that wildfires would respond to future warming similar to its manner during the past century. Reported fire cycle was around 40−150 years in the west taiga shield ecozone for the past century (Table 1), and an increase of growing season mean temperature by 1.86–2.75°C and about 5% increase of precipitation with respect to the 1961-1990 normal (Table 4) would result in a fire cycle of 80−140 years in the region. Similarly, we estimated, using Eq. 2, that fire cycle would be more than 700 years in the east boreal shield and east taiga shield. Projected fire cycles ranged from 300 to 400 years using scenarios of CGCM2 and HadCM2 in the boreal plains ecozone. However, estimated fires cycle was negative using scenario CGCM1. Of course, the result was unrealistic and due to the smaller increase of precipitation form scenario CGCM1 (Table 4). Overall, these estimates seemed to well correspond to those derived from fire weather index (Flannigan and van Wagne 1991; Weber and Flannigan, 1997; Flannigan *et al*. 1998). It should be pointed out that the projected fire cycles were averages for the ecozones. At a specific location within the ecozones, fire cycle might be different dependent upon the heterogeneity of landscape and spatial variability in the magnitude of climatic changes (e.g., temperature and precipitation) (Price *et al*. 2001).

Table 4. Climate change scenarios

Ecozone (ESWG 1996)	Temperature departure from the 1961-1990 normal (°C)						Precipitation departure from the1961-1990 normal (%)		
	CGCM1GSAX		CGCM2GSA2		HadCM2GSAX		CGCM1GSAX	CGCM2GSA2	HadCM2GSAX
	Maximum	Mean	Maximum	Mean	Maximum	Mean			
West Taiga Shield	2.60	2.75	2.40	2.56	1.74	1.86	6.75	3.61	7.22
Borel Plain	2.63	2.57	2.24	2.35	1.67	1.93	1.99	12.10	7.76
East taiga shield east boreal shield	2.13	2.28	2.13	2.29	1.54	1.67	6.81	8.43	10.16

Studies revealed changes of species distribution ranges and disturbance regimes in response to climatic change in the past (Overpeck *et al*. 1990; Davis *et al*. 2001), and few assessments indicated shifts of the Canada's boreal forest responsive to further climatic warming (Emanuel *et al*. 1985; Rizzo *et al*. 1992). However, shift in ranges of species distribution is generally slower than the current climate warming (Davis 1989) and focus needs to be on the species survival in the current range and migration to new locations (likely northwards). Changes in fire cycles as indicated in this study determine how long an individual plant can grow and become maturity before next fire returns. Thus, investigating the response of ecosystems to climatic change must incorporate changes of fire cycle.

The number of fire cycle studies limited this approach especially where there were too few studies in some ecozones to develop relationships between fire cycle and climatic variables. The on-going development of the Canada's large-fire database (Amiro *et al*. 2001) will provide an opportunity in quantifying changes in fire cycles over the past century. Time series analysis over different time periods and spatial extents (e.g., ecozone) (Baker 1989) could be employed to develop such relationships and generated a fire cycle "surface" for the Canada's boreal region. That would help in incorporating changes of fire cycles into the study of terrestrial carbon budget (Kabiski *et al*. 1995; Chen *et al*. 2000) and in formulating forest resources management strategy (Bergeron *et al*. 1993; Gauthier *et al*. 1996; Bergeron *et al*. 2001; McRae *et al*. 2001; Harvey *et al*. 2002).

Conclusions

In Canada's boreal forest region, there have been changes in fire cycles over the past century and those changes were attributable to climatic change and human interventions. Three epochs, namely pre-Little Ice Age (c. 1850), pre-settlement (c. 1850-1930), and fire suppression era (c. 1930), could be recognized with respect to the stationarity of fire cycles. However, difference in fire cycles between pre-Little Ice Age and settlement was not significant. Regression analyses indicated that fire cycles in four ecozones namely, west taiga shield, boreal plains, and the combination of east taiga and boreal shield, were relating to the growing season (April-October) temperature and precipitation departure from the 1961−1990 normal. Assessment of climate change demonstrated that fire cycle would be shortened in the west taiga (50–60 years) and boreal plain (300 years) and lengthened in the east region (700 years).

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